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Human-Robot Collaborative Manufacturing using Cooperative Game: Framework and Implementation

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Abstract

Human-robot collaborative manufacturing (HRC-Mfg) is an innovative production mode, however currently the theoretical explanation for the collaboration mechanisms is limited. Considering the dynamics and uncertainties in manufacturing environment, it is also crucial for both task allocation and decision-making. In the sight of cyber-physical production system, based on bilateral game and clan game, this paper presents the characteristics of HRC-Mfg and demonstrates the applicability of cooperative game in such system. Moreover, we also develop a framework and approach to describe how the mechanism works in detail. The case study shows it can dynamically arrange procedures and maximize the production benefit.

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Keywords: *Human-Robot; Collaborative Manufacturing; Mechanism Explanation; Cooperative Game*

1. Introduction

Human-robot collaborative manufacturing (HRC-Mfg) is an innovative production mode integrated with the concept of human-robot collaboration (HRC). While HRC has been proposed in different fields and gradually applied to specific manufacturing tasks, mainly reflected in three aspects.

i) Advanced robot design and manufacturing company like ABB, KUKA and Rethink Robotics have developed Yumi, iiwa, Sawyer, Baxter and other collaborative robots. ii) Scientific research institutions and universities use new technologies to update traditional robots with more collaborative potential [1-3]. iii) ISO has developed ISO/TS 15066, the latest collaborative robotics standard [4].

HRC has been putting forward constantly both in industry and academic because:

(1) The variety of products is abundant.

In the past decades of years, industrial robots are widely used in product manufacturing, especially in the traditional ones such as automobile manufacturing, food processing, electronic product manufacturing and chemical product production. With the continuous development of semiconductor technology, personal consumer electronics manufacturing enterprises such as Foxconn, Samsung, TSMC have become the emerging power in the manufacturing sector. On the other hand, due to the individual needs of product design of consumer market, manufacturing companies are pushed to continue to update the product type to seize the market opportunities. This requires product manufacturers to quickly and flexibly complete the switching and restructuring of their production line.

(2) The capability of traditional industrial robots is limited.

Traditional large-scale industrial robots are powerful to handle the packaging, transporting and other similar tasks. However, in the face of the sophisticated electronic products represented by smartphones and tablet PC, they are limited to participate in the manufacturing of precision components.

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Meanwhile, for the high complexity of the manufacturing tasks, small-scale industrial robots still cannot be as flexible as all the assembly process and testing.

(3) The development of remanufacturing is imperative.

Product disassembly is usually the first step in remanufacturing process and determines the efficiency and capability of remanufacturing [5]. For remanufacturing tasks in green manufacturing and sustainable manufacturing, it is very different from traditional new product manufacturing. The new product manufacturing process has detailed assembly plan and process. Its product parts and components are packaged in standardization. The assembly line only needs to install and attach the production components to the assembly object one by one according to the predetermined assembly plan and the fixed procedure. In this process, as long as the manufacturing object model is the same, all the robot program logic, the force control, or the manual operations are almost constant. But even if it is of the same type and the same batch of products, the individual differences could be extremely significant in the remanufacturing environment of disassembly, recycling and reuse of the old product.

However, as for HRC-Mfg, the theoretical explanation for the collaboration mechanisms is limited currently, especially combined with specific manufacturing tasks with complex environments or components. Considering the dynamics and uncertainties in the manufacturing environment, it is also crucial for both task allocation and decision-making.

Game theory includes cooperative game and non-cooperative game. The non-cooperative game is based on Nash equilibrium, which was put forward by John Nash from 1950 to 1952 [6]. It focuses on solving the game problem from a microscopic view. The cooperative game originated in the Nash bargaining problem [7], which is described as 'a game of cooperation agreement'. It focuses on how to maximize the interests of the participants in the game and how to distribute the benefits for each participant. Recently, game theory had been implemented in HRC [8-10], but seldom deployed in the HRC-Mfg.

In the sight of the cyber-physical production system (CPPS), based on the bilateral game and clan game, this paper presents the characteristics of HRC-Mfg and demonstrates the applicability of cooperative game in such system. Moreover, we also developed a framework and approach to describe how the mechanism works in detail with a case study.

The remainder of this paper is organized as follows. Section 2 presents the characteristics of HRC-Mfg and cooperative game theory in manufacturing. In section 3, the framework of mechanism interpretation for HRC-Mfg is delivered. Section 4 is the implementation and case study. Section 5 concludes this paper.

2. Characteristics of HRC-Mfg and cooperative game theory in manufacturing

2.1. Human-Robot Collaborative Manufacturing System

We define human-robot collaborative manufacturing system (HRCMS) as a special manufacturing system based on CPPS. Apart from the numerical control equipment matched with the manufacturing cell, traditional manufacturing systems do not have integrated information systems oriented to the production line, workshop, and enterprise level. CPPS abstracts the physical resources in the manufacturing environment into virtual models through intelligent perception [11-13]. Then the operation and evolution of the manufacturing system are reproduced in the virtual world. HRCMS can realize the information interaction between the human and the robot individual based on the virtual model of CPPS and the perception and cognition of human behaviors and actions. The data from CPPS can support the decision-making system of HRCMS, and finally realize the task of man and robot together. In short, CPPS is the premise of HRCMS, HRCMS is the expansion and specialization of CPPS.

2.2. Characteristics and requirements of HRC-Mfg

For HRC-Mfg due to the dynamics and uncertainties in the manufacturing environment, it is crucial but difficult to study the task allocation and dynamic scheduling between human and robot in combination with specific manufacturing environment and tasks.

The challenge of HRC-Mfg and HRCMS mainly comes from the following characteristics:

- **Dynamism and uncertainty.** The production line, products, human behavior and industrial robot movements of HRC-Mfg are dynamic and uncertain, they will impact the results of the original decision.
- **Highly real-time.** HRCMS must have high real-time due to the stringent requirements of the production rhythm in manufacturing workshop and production line.
- **Parallelism and inequality.** HRC-Mfg efficiency reflects the corresponding manufacturing tasks can be executed in parallel by the human and the robot. In the process of HRC-Mfg, industrial robots are unequal to human workers both in decision and action.
- **Limitation of ability.** HRCMS must take the ability limitation of the human and the robot into consideration.
- **Repetition of decision with multiple constraints.** The decision-making results for the manufacturing process of each individual according to the real status of the repeated decision do not have the same. It also has multiple types of constraints, such as interactive security constraints, working time constraints, time cost constraints, and quality assurance constraints.
- **Tolerance of fault.** HRCMS should be tolerant to the delay and the fault generated by human behavior and action.
- **Backward mechanism.** HRC-Mfg embodies different procedures with different decisions. It is obvious that the current decision will have an impact on future decisions without affecting prior ones.

In combination with the features mentioned above, an HRCMS needs the following capabilities:

i) Capability for manufacturing task decomposition and procedure allocation.

ii) Capability to perceive and analyze manufacturing objects' status.

iii) Capability for perception, cognition, analysis, and decision-making of human activities.

iv) Friendly human-robot collaborative interfaces.

v) Capability to make a real-time intelligent decision for whole manufacturing task.

Obviously, HRCMS is a highly complex dynamic decision system involving multiple agents. In order to solve the above challenges, it is crucial to interpreting the mechanism for HRC-Mfg in a clear, detailed, and scientific way.

2.3. Cooperative Game Theory in Manufacturing

The mechanism of HRC-Mfg can be interpreted by cooperative game theory, which is mainly embodied in the following aspects:

(1) HRC-Mfg satisfies the premise of the game.

One game requires at least two participants. Otherwise, it does not constitute a game. HRC-Mfg involves at least one industrial robot and a worker to work with it, which is consistent with the premise of the game.

(2) HRC-Mfg satisfies the premise of the cooperative game.

The premise of the formation of a cooperative game is that the benefit of participants through the cooperative game is higher than that obtained by independent work. Otherwise, participants will abandon cooperation. Accordingly, manufacturing enterprises can only adopt HRC-Mfg when they can use HRC to improve production efficiency and reduce costs. In other words, as long as the HRC-Mfg is adopted, we must ensure that it can bring more benefits for enterprises. So we can use the cooperative game to describe the mechanism of HRC-Mfg.

(3) HRC-Mfg has the characteristics of strong and weak complementation and distribution according to work.

The cooperative game allows the participants to be unequal in their ability and distribute the benefits according to the contributions of different participants. In HRC-Mfg, in the face of different manufacturing objects and procedures, industrial robots and human workers have their own advantages and disadvantages, and also show their importance to different procedures.

3. Framework and operation mechanism of HRC-Mfg

3.1. Task Decomposition and procedure allocation

In the process of HRC-Mfg, we consider that industrial robots and human workers should be responsible for different procedures. The robot and human procedure set are required to be described in advance according to the robot and human ability characteristics and specific manufacturing tasks.

Fig. 1 shows a process structure example of a disassembly task. A disassembly task takes the pick-up procedure as the start of one task and regards the stock procedure as the last step of it.

In this paper, the total procedure set is denoted by S, the robot and human procedure set are denote by R and H. Obviously, for the specific procedures, some need to be done by people, while others need to be handled by robots. That is, there should be no procedure beyond the capability of robot or human, or a manufacturing task with different procedures should be able to be completed under the collaboration of the robot and the human.

Above all, one equation should be satisfied: $R \bigcup H = S$. From the point of view of manufacturing capability, $\overrightarrow{R}$ is defined as the robotic procedure vector, while $\overrightarrow{H}$ is the manual procedures vector and $\overrightarrow{U} \triangleq \overrightarrow{R} + \overrightarrow{H}$ is the check vector. From the other point of view of manufacturing task, $\overrightarrow{R_P}$ is denoted as the selected robotic procedures vector, $\overrightarrow{H_P}$ is denoted as the selected manual procedures vector and $\overrightarrow{U_P} \triangleq \overrightarrow{R_P} + \overrightarrow{H_P}$ is used as the selected check vector. It is clear for a fully allocated manufacturing task to satisfy $\overrightarrow{U_P} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & \cdots & 1 \end{bmatrix}_n$ and $n = N(\overrightarrow{U_P})$ equals to the total number of operations for the manufacturing task. In order to ensure the completeness of the manufacturing task, the check vector $\overrightarrow{U}$ must be approved on the basis of the complex graph or semantic model. With the progress of manufacturing tasks, the procedures in $\overrightarrow{R}$ and $\overrightarrow{H}$ are iteratively selected into $\overrightarrow{R_P}$ and $\overrightarrow{H_P}$. The selected check vector $\overrightarrow{U_P}$ of every iteration needs to be checked to guarantee the completeness of the procedures.

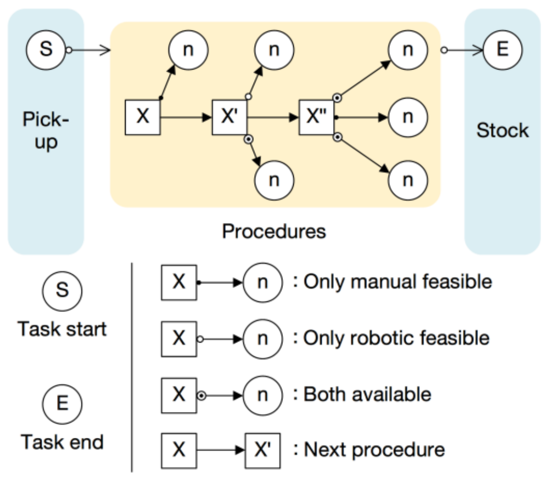

Fig. 1. Task decomposition and procedure allocation for disassembly.

In procedure allocation, any $(\overrightarrow{R_P}, \overrightarrow{H_P})$ is a Nash equilibrium ($\vec{0} < \overrightarrow{R_P} < \overrightarrow{U_P}, \vec{0} < \overrightarrow{H_P} < \overrightarrow{U_P}$). As for a manufacturing task denoted by $N(\overrightarrow{U_P}) = n$, it has 2^n common species with exponential growth. HRCMS needs to find an optimal configuration according to the working status of human and robot so that both they can get the highest efficiency and the lowest cost in the following procedures.

3.2. Cooperative game for human-robot collaborative model with multiple procedures

In HRC-Mfg, the deployment contains various forms including 'one-human-one-robot', 'one-human-multi-robots', 'multi-humans-one-robot' and 'multi-humans-multi-robots',. This paper takes 'one-human-one-robot' as an example to describe the combination of cooperative game.

In the principles introduced earlier, it is obviously difficult to find an optimal solution on a large scale such as an exponential model, which is called the multiple equilibrium problems in the traditional non-cooperative game. One of the most important ways to solve this problem is Schelling's theory of focalization. By setting up the focus arbiter, it guides the game players to focus their attention on a particular equilibrium, which is the optimal direct solution in HRC-Mfg. There is a kind of special focus arbiter in the theory of focalization, which is itself the player of the game. In HRC-Mfg, the HRCMS that the industrial robot connects is responsible for the game solution, and then the robot can be regarded as a special focus arbiter.

As the Fig. 2 shows, the procedure decomposition problem in one-human-one-robot collaborative manufacturing is a typical substantive bilateral cooperative game. And the procedures allocation is a typical clan cooperative game. To explore the mechanism of that, it is necessary to establish two models of the bilateral game and the clan game.

In this paper, the bilateral game refers to the cooperative game with only two participants. The total utility of cooperative game is considered as $v(\{r,h\})$, and the utility of robot is given as x_1. According to the premise of the cooperative game, it should not be less than the benefit $v(\{r\})$ when robot completes a manufacturing task independently. It's same to the utility of human workers and we define it as x_2.

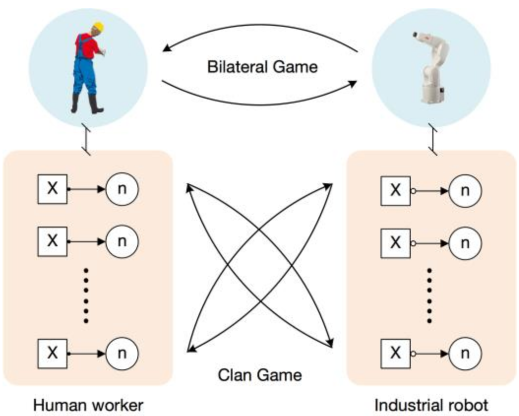

Fig. 2. Cooperative game for HRC-Mfg with multiple procedures.

Clearly, it can be written as $x_1+x_2=v(\{r,h\})$ and this equation can also be rewritten as $x_1+x_2=v(\overrightarrow{R_P},\overrightarrow{H_P})$ to correspond to the procedures vector in the previous section. These (x_1,x_2) constitute a utility allocation. All (x_1,x_2) form the feasible collocation set F of the cooperative game. According to the characteristics of human-robot collaboration, one (x_1,x_2) has two obvious poles, namely $(v(\{r,h\}),0)$ and $(0,v(\{r,h\}))$.

For the procedures allocation derivation of HRC-Mfg, first of all, the procedure cost is required to be associated with the utility. We denote the common cost of human and robot in HRC-Mfg as $c(\{h,r\})$ and the cost of human and robot are separately x_h and x_r respectively, then all the configurable sets are formed as F, with extremes $(x_h,0)$ and $(0,x_r)$. For a one-human-one-robot cooperative game procedure allocation problem (F,e), it can be modeled as (1) with the inability to reach an agreement $(e_h,e_r)=(x_h^{-1},x_r^{-1})$.

$$F\cap\{(x_h^{-1},x_r^{-1})\,|\,x_h^{-1}>e_h\ \&\ x_r^{-1}>e_r\} \tag{1}$$

It is a cooperative game of substantial essential. According to Nash axiom, the Nash solution of the game is (2).

$$\Phi(F,e)=\underset{x^{-1}\in F,x^{-1}>e}{\arg\max}(x_h^{-1}-e_h)(x_r^{-1}-e_r) \tag{2}$$

The cost function of the allocation scheme can be set according to the specific manufacturing tasks, such as by different indicators (like time cost $ti(x)$, energy cost $ec(x)$ and so on) in the weighted sum form (3).

$$c(x)=\lambda_1\cdot ti(x)+\lambda_2\cdot ec(x)+\cdots+\lambda_n\cdot other(x) \tag{3}$$

In addition to Nash solution, there are also egalitarian solutions, utilitarian solutions, Kalai-Smorodinsky solutions and so on. The algorithm for cost allocation in HRC-Mfg should select a suitable solution according to specific manufacturing task and environment.

After assigning the related procedures to the human and the robot, it is necessary to schedule them in sequence. The HRC-Mfg with one-human-one-robot form has the characteristics of mixed execution. That is the manual procedures and the robot procedures are executed serially, but both of them constitute the relationship of parallel execution. Due to the dynamic nature of HRC-Mfg, after every procedure is executed, the subsequent procedure sequence needs to be rearranged immediately. The clan game for procedure set is to solve the problem of how to schedule so that humans and robots can spend less on subsequent procedures.

The Weber set in cooperative games is a mathematical model related to the order of participants in a cooperative game. We consider N_H and N_R be the number of the manual procedures and robotic procedures to be scheduled, $N_H=N(\overrightarrow{H_P})$ and $N_R=N(\overrightarrow{R_P})$. Both of them are a Weber set and constitute an clan cooperative game $v\in G^N$.

Take the robotic procedures as an instance, N_R procedures constitute $N_R!$ permutations together, and the set of all $N_R!$ permutations is donated as $\pi(N_R)$, each permutation is defined as $\sigma \in \pi(N_R)$ with the procedure sequence $(\sigma(1), \sigma(2), \cdots, \sigma(n))$.

For each procedure $\sigma(i)$, we denote the cost function as $d(\sigma(i)) \in (0, \Delta)$, the dynamic factor as $\varepsilon_i \in (0,1)$, the priority constant as p_i, the common difference of priority as Δ, respectively, the direct cost of the procedure, the cost impact by the HRC status, this procedure in the task's priority and the tolerance of the priority constant sequence. Finally, we construct function (4) as the cost function for this procedure in the clan.

$$c(\sigma(i)) = p_i + \varepsilon_i \cdot d(\sigma(i)) \tag{4}$$

For each determined permutation, a vector that depends on the permutation is constructed so that N_R procedures could enter the permutation step by step. We consider the cost of $\sigma(1)$ is $c(\sigma(1))$ .After $\sigma(2)$ enters the game, the cost of their clan becomes $c(\sigma(1), \sigma(2))$. And so on, the marginal cost of each procedure in this clan can be expressed as function (5).

$$m^{\sigma}_{\sigma(N_R)}(c) = c(N_R) - c(\sigma(1), \sigma(2), \cdots, \sigma(N_R - 1)) \tag{5}$$

All marginal costs of each procedure in the function above constitute the marginal vector (6) of this clan cooperative game.

$$m^{\sigma}(c) = \left\{ m^{\sigma}_{\sigma(1)}(c), m^{\sigma}_{\sigma(2)}(c), \cdots m^{\sigma}_{\sigma(N_R)}(c) \right\} \tag{6}$$

It is related to permutation σ clearly, and $N_R!$ permutations have $N_R!$ different marginal vectors. The convex hull of all $m^{\sigma}(c)$ constitutes the Weber set of the game, we donate it as $W(c)$. In this way, the optimal arrangement of robot procedures can be equivalent to finding one σ in $\pi(N_R)$ to minimize the corresponding $m^{\sigma}(c)$, that is, solving the equation (7).

$$\Phi(\pi(N_R), W(c)) = \underset{c \in G^{N_R}, \sigma \in \pi(N_R)}{\arg\min} \left| m^{\sigma}(c) \right| \tag{7}$$

4. Case study

Taking the disassembly task of 'bolt type roller bearing' as an example, a case study of HRC-Mfg based on the cooperative game is presented. A roller bearing shown in the Fig. 3 contains 6 parts. For each bearing disassembly task, in addition to the starting step S and the end step E, there are 6 subprocedures, $N(\overrightarrow{U_P}) = 6$. As shown in the Fig. 3, n_1 is a procedure that can only be done manually, n_3 is a procedure that can only be done by robots, and the rest can be done by both of them. Therefore, the procedure vector can be obtained as $\vec{H} = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 & 1 \end{bmatrix}$, $\vec{R} = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$ and $\vec{U} = \vec{H} \cup \vec{R} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$. It's clearly satisfied with $H \cup R = S$ and all elements of $\vec{U}$ are 1. So the current HRC-Mfg task is complete.

Given the $N(\overrightarrow{U_P}) = 6$, the bilateral game has $2^6 = 64$ equilibria, but because the allocation scheme of n_1 and n_3 is fixed, there are actually $2^4 = 16$ alternative equilibria. In order to facilitate the calculation, we assume $c(\{h\}) = 50$, $c(\{r\}) = 40$ and the extreme point is $(e_h, e_r) = (0.02, 0.025)$. Calculating the 16 allocation schemes iteratively with function (8),

$$\Phi(F, e) = \underset{x \in F, x^{-1} > e}{\arg\max} (x_h^{-1} - 0.02)(x_r^{-1} - 0.025) \tag{8}$$

the lowest cost allocation scheme is obtained, which corresponds to a $(\overrightarrow{H_P}, \overrightarrow{R_P})$, and it needs to be tested again. Suppose the allocation scheme obtained by bilateral cooperation game is $\overrightarrow{H_P} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 1 \end{bmatrix}$ and $\overrightarrow{R_P} = \begin{bmatrix} 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix}$ with completed procedures.

In the clan game of procedure permutation, there is $N_H = N_R = 3$. We take $N_R = 3$ as an example to calculate, and there are 6 permutations. It can be found in the Fig. 3 that 'bolt type roller bearing' disassembly have 3 priorities, respectively $\{n_1\}, \{n_2, n_3\}, \{n_4, n_5, n_6\}$. For robotic procedures, all permutations are listed in function (9).

$$\begin{aligned} \pi(N_R) = \{ &(n_2, n_3, n_5), (n_2, n_5, n_3), (n_3, n_2, n_5), \\ &(n_3, n_5, n_2), (n_5, n_2, n_3), (n_5, n_3, n_2) \} \end{aligned} \tag{9}$$

We assume that the weights of the three priorities are 1, 6 and 11 ($\Delta = 5$) respectively. The n_2, n_3, and n_5 procedures are represented as $\sigma(2)$, $\sigma(3)$ and $\sigma(5)$. $d(\sigma(i)) = \begin{bmatrix} 4 & 3 & 4 \end{bmatrix}$ and $\varepsilon_i = \begin{bmatrix} 0.8 & 0.5 & 0.6 \end{bmatrix}$ are assumed to be calculated. We might as well define one of the simplest marginal vector operations as function (10).

$$\begin{aligned} m^{\sigma}_{\sigma(k)}(c) &= c(\sigma(1), \sigma(2), \cdots, \sigma(k)) \\ &- c(\sigma(1), \sigma(2), \cdots, \sigma(k-1)) = c(\sigma(k)) - c(\sigma(k-1)) \end{aligned} \tag{10}$$

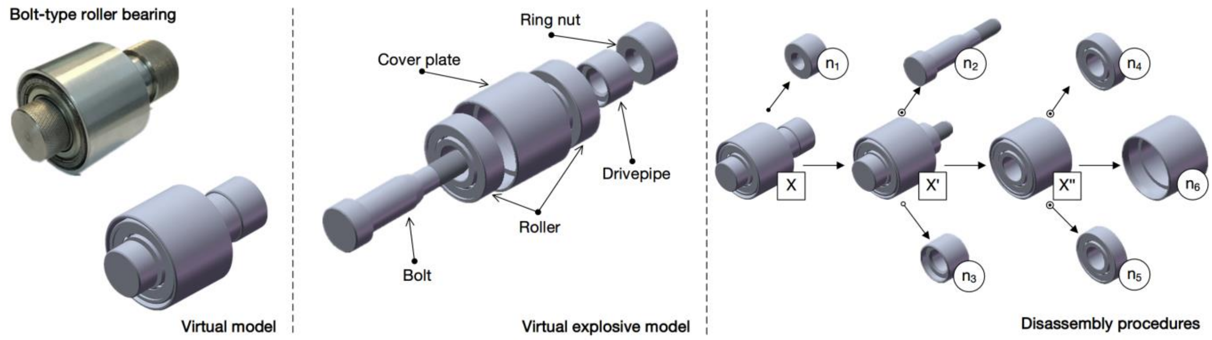

Fig. 3. Bolt type roller bearing disassembly task.

Finally, we can get the result in Fig. 4 from the calculation. Obviously, $\pi(N_R)=(n_3,n_2,n_5)$ is the optimal solution under the current conditions.

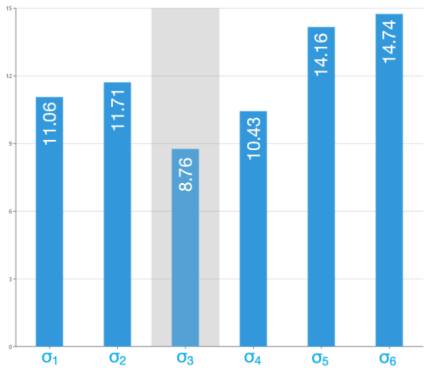

Fig. 4. Case study result.

By observing the results of this clan game, it can be found that the optimal solution not only meets the requirements of procedures' priority but also can correspond to the real-time HRC-Mfg status based on the cost function of the procedures.

5. Conclusion and future work

This paper proposed problems with the explanation of the mechanism of HRC-Mfg and summed up characteristics of it. We for the first time used the cooperative game theory in HRC-Mfg, put forward the framework of procedure allocation and permutation and explained why the cooperative game is suitable for HRC-Mfg with the case study demonstrated its practicality.

In future work, we will conduct mathematical modeling of 'multi-humans-multi-robots' production line based on algorithm design and implementation. In addition, we will consider more realistic manufacturing situations, such as the iterative game mechanism when a manufacturing task is repeated, and interpret it with the theory of knowledge evolution.

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